Climate-Resilient Horticulture: Adapting to climate change through Innovative Practices and Technologies

Abstract

Climate change poses significant threats to horticulture, impacting crop yields, quality, and overall agricultural sustainability through increased temperatures, irregular rainfall, and extreme weather events. To address these challenges, climate-resilient horticulture leverages innovative practices and technologies. Key approaches include the development of heat-resistant, drought-tolerant, and salt-tolerant crop varieties, which enhance the resilience of plants to harsh environmental conditions. Advanced water management strategies, such as drip irrigation and rainwater harvesting, are essential for conserving water and ensuring consistent moisture supply. Soil management practices, including organic amendments and conservation tillage, improve soil health and fertility, aiding in climate adaptation. Technological advancements like precision horticulture enable farmers to optimize inputs and reduce waste, while Controlled Environment Agriculture (CEA) systems, including greenhouses, hydroponics, allow for the cultivation of crops in regulated environments, minimizing external climate impacts. Additionally, genetic engineering and biotechnology offer promising solutions for developing crops with enhanced climate resilience. Despite the potential of these innovations, challenges such as high costs, knowledge barriers, and policy constraints must be addressed to facilitate widespread adoption. This abstract underscores the necessity of integrating these strategies to secure the future of horticulture in a changing climate, ultimately contributing to global food security and agricultural sustainability.

Keywords: Resilience, climate impact, technological advancements, greenhouses, challenges

1. Introduction

1.1 Overview: Impacts of climate change on Horticulture:

Climate change, encompassing rising temperatures, altered rainfall patterns, sea level rise, saltwater intrusion, and the occurrence of floods and droughts, is acknowledged as a global concern (Bates *et al.*, 2008). Climate change poses significant challenges to global agriculture, particularly to horticulture, which is highly sensitive to climatic variations. Rising temperatures, changed precipitation patterns, and an increase in the frequency of extreme weather events highlight how urgent it is to implement climate-smart techniques since they all represent serious risks to conventional horticulture systems (Lobell *et al.,* 2019). In order to fully address these issues, Climate-Smart Horticulture promotes a proactive and adaptable strategy. Important elements of the Climate-Smart Horticulture framework include resilient crop varieties, precision agricultural technology, water-efficient irrigation systems, soil health management, and integrated pest control (Smith *et al.,* 2021; FAO, 2020).

The dynamics of pests are greatly impacted by climate change, which is a major factor in the transformation of ecosystems. Variations in temperature, patterns of precipitation, and extreme weather have a direct impact on pest distribution, abundance, and behavior. (Ainsworth and Lemonnier, 2008) have noted that changes in climate can have an impact on the availability of host plants, upsetting the delicate ecological balance between pests and their natural adversaries. (Lemonnier and Ainsworth, 2008) The sector, encompassing fruits, vegetables, flowers, and ornamental plants, plays a crucial role in nutrition, livelihoods, and cultural practices worldwide. However, its dependency on specific climatic conditions makes it vulnerable to climate-induced stresses such as drought, heatwaves, and unpredictable rainfall (Kumar *et al.*, 2019). To address these challenges, the concept of climate-resilient horticulture has emerged, emphasizing the integration of innovative practices and technologies that enhance the resilience of horticultural systems.

1.2 Climate resilience

The ability of a system and its constituent parts to predict, absorb, accommodate, or recover from the consequences of a hazardous event in a timely and effective manner, including ensuring that its fundamental structures and functions are preserved, restored, or improved, is known as resilience (IPCC, 2012). It refers to a system's capacity to withstand shocks and quickly return to normal when the outside environment gets better.

1.3 Importance of Climate-Resilient Practices

A systematic and comprehensive approach to horticultural operations, Climate-Smart Horticulture (CSH) places an emphasis on resilience, sustainability, and flexibility in the face of changing climatic circumstances. The process entails the amalgamation of cutting-edge technology, eco-friendly farming methods, and flexible approaches to maximize resource efficiency, reduce ecological footprints, and guarantee the sustained prosperity of horticulture production networks. The value of CSH is in its ability to increase horticulture crops' resistance to climate-related challenges, safeguarding global food production, sustaining livelihoods, and advancing nutritional objectives and food security. These strategies include the development of drought-tolerant crop varieties, the implementation of water-efficient irrigation systems, the use of climate-smart soil management techniques, and the adoption of controlled-environment agriculture. Additionally, advances in digital agriculture, such as precision farming and real-time climate monitoring, offer new avenues for mitigating the impacts of climate change on horticulture.(Lobell *et al.,* 2019)

The adoption of climate-resilient horticulture is not just a matter of necessity but also of opportunity.A paradigm change in agricultural methods has occurred during the last several decades as a result of temperature changes, changing precipitation patterns, and an increase in the frequency of extreme weather events (Vermeulen *et al.,* 2012). By investing in these practices, farmers can reduce their vulnerability to climate risks while simultaneously increasing productivity and sustainability. Moreover, such approaches contribute to the broader goals of sustainable development, ensuring that horticultural production can continue to meet the demands of a growing global population despite the challenges posed by a changing climate.

Table 1: Annual temperature increase across different zones of India (H.P. Singh *et al.*, 2013)

S. No.	Indian zones	Temperature increase (°C)		
		Max. T (°C)	Min. T (°C)	Mean T (°C)
1.	All India	0.76°C	0.22°C	0.49°C
2.	Northeast India	1.04°C	0.19°C	0.63°C
3.	Northwest India	0.55°C	−0.14°C	0.20°C
4.	North Central India	0.74°C	0.26°C	0.49°C
5.	East Coast of	0.67°C	0.36°C	0.52°C

	India			
6.	West Coast of India	1.24°C	0.22°C	0.73°C
7.	Western Himalayas of India	0.93°C	0.48°C	0.70°C
8.	Interior Peninsular India	0.53°C	0.45°C	0.49°C

2. Studies of Impact and Adaptation in Horticultural Crops: current status

2.1 Fruit crops:

Large expenditures are required to construct perennial fruit crop orchards; the stressors brought on by climatic fluctuation would affect productivity year over year, significantly affecting the farmer's decision to continue producing such crops in the long term and his revenue. Farmers would be forced to stop planting these crops entirely after experiencing consistent losses for a few years. Farmers in Himachal Pradesh are being forced to switch to growing other income crops because of the state's rising average temperature, prolonged summer droughts, and decreased winter snowfall. Most of the state was previously considered moderately suited for apple farming. The state's farmers have switched to growing vegetables like tomatoes and peas due to the negative effects of apple production in the lower regions of the Kullu and Mandi districts. The apple field in the Sirmaur district's Rajgarh region has been converted to peach. It has been noted that mango and guava suffer significant harm from the extreme weather incidents of hot and cold waves. The most frequent meteorological variables that citrus crops encounter are delayed monsoons, dry spells, and unexpected rainfall during the water stress period that is applied to induce flowering, as well as higher temperatures during flowering and fruit growth. In general, banana plants mature more quickly at temperatures between 31 and 32°C, which reduces the bunch development time (Turner *et al.* 2007), (Singh *et al.*1966). Drought and extreme temperatures (over 38°C) can also cause bunch choking (Stover and Simmonds 1972).

2.2 Vegetable crops:

Research has shown that early onion crop development induced by soil water stress resulted in a 26 percent reduction in production. According to (Srinivasa Rao, 1995), water stress and temperatures over 28°C caused a 30-45%–45% lower decline in tomato yield across several varieties. The introduction of cultivars resistant to drought and rainfall, such as tomato variations Arka Vikas, onion types Arka Kalyan, and chilli variety Arka Lohit, has helped mitigate the issue of moisture stress. RF-4A in tomato, MST 42 and MST 46 in onion, and IIHR Sel. 132 in chilli, are a few advanced lines identified as possessing drought resistance. (Anonymous, 2011). Higher temperatures in tomatoes can result in smaller, lower-quality fruits, decreased fruit set, and significant production losses. According to reports, the ideal daily mean temperature for tomato fruit set is between 21 and 24°C (Geisenberg and Stewart 1986). In tomatoes, the pre-anthesis period is more delicate. Pepper fruit set is inhibited by high temperatures after pollination, suggesting that the fertilization mechanism is sensitive. The expression of sex in cucumber is influenced by temperature. High temperatures result in the creation of more male flowers, whereas low temperatures encourage the ideal generation of female flowers. High temperatures abbreviate the onion's growing season, which lowers yields.

2.3 Spices and Plantation crops:

The majority of the coconut-growing regions are showing a general warming trend, according to research done at the Central Plantation Crops Research Institute in Kasaragod (Naresh Kumar *et al.*, 2007). With the exception of a recent downward trend in the Maidan region of Karnataka and Coimbatore, Tamil Nadu state, due to repeated droughts, coconut output has improved during the previous 50 years. For four years, the production was down by around 3,000,00,000 nuts annually. Since cashew is mostly produced in rain-fed environments, it is susceptible to drought conditions brought on by changes in rainfall patterns and other climatic fluctuations. Unseasonal rainfall and thick dew during the flowering and fruiting stages increase the prevalence of pests and illnesses. They also minimize pollinating insect activity, which leads to inadequate nut setting. In addition, the rains that fall during the harvest season cause the nuts to soak and have an impact on the quality and shelf life of the nuts. Unseasonal rains during the ripening period cause the apples on trees to decay and the nuts to become black. (Yadukumar and others, 2010). At the Indian Institute of Spices Research in Calicut, geographic information systems (GIS) were utilized to analyze the impact of meteorological parameter changes on ginger and black pepper. According to the Eco-crop model of DIVA GIS, most of the locations where these crops are grown may become unsuitable for cultivation with a 2°C increase, while some new places may become appropriate for cultivation (Krishnamurthy *et al.*, 2010).

3. Innovative Approaches to Climate-Resilient Horticulture

Even though climate change is happening, CO2 and methane levels are expected to rise, which might affect temperature, increase water demand, and intensify biotic and abiotic stressors. Apple blossoming won't be sufficiently induced by mid-hill cooling, and high temperatures can cause pollen desiccation and fruit shriveling, lowering yield and increasing crop failure. These are the anticipated effects that give rise to the worries. However, there are countless instances when the environment has changed and technological advancements have assisted in reducing the issue. Cauliflower, potatoes, tomatoes, and cabbage are examples of thermosensitive crops that can only produce well in temperate climates with long days. However, it is now feasible to achieve extremely high output even in subtropical and mild subtropical temperatures, thanks to the introduction of heat-tolerant cultivars and modifications in production system management.

3.1 Heat resistant and Drought tolerant varieties

Heat resistance and drought tolerance are also important traits for horticultural crops, including fruits, vegetables, and ornamental plants. Breeding and selection efforts have led to the development of several varieties that can withstand these challenging environmental conditions. These garden cultivars have been created or chosen based on their capacity to withstand the damaging effects of heat and drought, promising yield and quality under harsh environmental circumstances. Here are some examples of heat-resistant and drought-tolerant horticultural varieties:

Table 2: Heat resistant and drought tolerant varieties

S.No.	Crops	Scientific name	Variety	Traits	References
1.	Tomato	*Solanum lycopersicum*	Solar Fire	This tomato variety is a heat-tolerant that can	(Foolad*et al.*, 2007)

				set fruit even at high temperature above 90°F (32°C). The variety is also moderately drought- tolerant.	
2.	Pepper	*Capsicum annum*	Carolina Wonder	This variety is both drought and heat tolerant. It performs well under high temperatures and low water conditions.	(Aloni, B., *et al.,* 2001)
3.	Pomegranate	*Punica granatum*	Ganesh, wonderful	These pomegranate varieties are well-suited to hot, dry climates and are well known for their drought resistance.	(Levin, 2006)
4.	Avocado	*Persea americana*	Bacon, Zutano	Compared to other types, these avocados can withstand higher temperatures and periods of drought. It is frequently advised to cultivate	(Michelakis, N., *et al.*, 1993)

				them in areas where water availability is unpredictable.	
5.	Citrus	*Citrus sp*.	Carrizo (rootstock)	Citrus species are grafted onto Carrizo, a drought-tolerant citrus rootstock. It can withstand certain amounts of heat as well.	(Castle, W. S., 2010)
6.	Grapes	*Vitis vinifera*	Grenache, Cabernet Sauvignon	These grape varieties are well-known for their capacity to withstand drought and bloom in warm, dry environments. Dry weather is very ideal for Grenache	(Hochberg, U., *et al.*, 2015)
7.	Olives	*Olea europaea*	Koroneiki, Arbequina	These olive varieties are highly drought-tolerant and can better survive in Mediterranean climates with least water.	(Gucci, R., *et al.*, 2019)

8.	Cucumber	*Cucumis sativus*	Tasty Green	This variety of cucumber is heat-tolerant known for its ability to produce fruit in high-temperature environments.	(Collado-González, J., *et al.*, 2021)
9.	Lettuce	*Lactuca sativa*	Sierra	Sierra is a heat-tolerant lettuce variety that can be grown in warmer climates where traditional lettuce varieties might bolt or fail to form heads.	(Jenni, S., *et al.*, 2013)
10.	Ornamental Plants	*Portulaca grandiflora*	Moss Rose	The drought-tolerant ornamental plant portulaca loves hot, dry weather. Its minimal water needs make it a popular choice for landscaping.	(Huang, B., *et al.*, 2005)

3.2 Salt Tolerant varieties

Salt tolerance is such a complicated genetic and physiological feature. Conventional breeding programs have had relatively little success improving it (Flowers, 2004). Effective screening techniques, the presence of genetic variety, and the capacity to transfer genes to the target species are necessary for successful salt tolerance breeding. Because field soils have varying salinity levels, it is not a recommended practice to screen for salt tolerance in the field. According to (Cuartero and Fernandez-Munoz, 1999), screening need to be carried out in soilless cultures using nutrient solutions with known salt concentrations. According to (Yildirim and Guvenc 2006), pepper genotypes Demre, Ilica 250, 11-B-14, Bagci Carliston, Mini Aci Sivri, Yalova Carliston, and Yaglik 28 may be good sources of genes for the development of pepper cultivars that germinate well when exposed to salt stress. When exposed to high salt treatments, the pepper cultivar Bendi in Tunisia produced noticeably more than other test cultivars. The propensity of tomato seeds to germinate quickly under salt stress is attributed to the S. esculentum accession (PI17426) (Foolad and Jones, 1991). AVRDC, Taiwan's tomato genotypes LA1579 and LA1606, which belong to S. pimpinellifolium, and LA4133, which belongs to S. lycopersicum var cerasiforme, have demonstrated resistance to salt.

3.3 Water Management Strategies

Since a lot of vegetables are consumed raw and possess a high water content, using good-quality water is still a big problem. Vegetable productivity and quality are determined by the effectiveness and caliber of water management. In addition to causing irregular plant development and predisposing plants to pathogen infection, excessive or insufficient watering can also lead to nutritional problems. The most crucial agronomic measures to preserve yields under drought stress are timely irrigation and soil moisture reserve conservation if water is limited and supplies are irregular or unpredictable. There are several ways to apply irrigation water, and the method that we choose will rely on the crop, the availability of water, the properties of the soil, and the geography. Although more than 80% of the world irrigated areas use surface irrigation techniques, their field-level application efficiency is frequently below 40% to 50% (Von and Chieng, 2004). Temperature increases frequently trigger modifications in the hydrological cycle that accelerate the rates of rainfall and evaporation. According to (Schulze, 2011), rising temperatures may affect patterns of precipitation, runoff distribution (both geographically and temporally), groundwater reserves, soil moisture, and the frequency of drought and flood occurrences. Thus, temperature variations directly affect India's capacity to access water resources. Studies on climate variability and change are especially crucial for the Indian subcontinent since progress in the economy and society depends on rainfall. The country's climate has a significant impact on how well water resources operate. During the four monsoonal months, around 80% of the rainy season falls, however it may not even be evenly distributed which causes scarcity in many areas. To meet demand during the dry season, therefore, large water storage facilities are needed (Mehrotra & Meh rotra, 1995). There is evidence of how climate change affects the basin's water balances. On the other hand, how and if communities are influenced in such changing locations depends in part on land use and water management patterns (Hagemann *et al.,* 2013).

Drip Irrigation/ Micro-Irrigation: Micro irrigation and trickle irrigation are other names for drip irrigation. By using a system of emitters, pipes, valves, and tubing to let water trickle gradually close to the plant roots, this irrigation technique gives a farmer control over how much water and fertilizer is applied. When compared to the majority of conventional surface irrigation techniques, it reduces water losses from runoff and deep percolation and yields water savings of 50–80%. When drip irrigation was used instead of furrow irrigation, pepper chilli plants used much less water. Greater delivery rate drip irrigation regimes were associated with these greater efficiency levels (AVRDC, 2005). N2O losses in melon crops grown with drip irrigation were lowered by 70% (Sanchez-Guerrero *et al.,* 2009).Higher water consumption efficiencies were obtained by applying drip water from the surface-irrigated drip system below the surface (Sharma *et al.* 2005, 2011). A well-managed drip irrigation system can improve tomato quality while conserving water (Rudich *et al.* 1977). Tomatoes have varying water needs depending on the stage of the crop; consequently, the best irrigation schedule should be determined to satisfy the plant's water requirements.

Rainwater Harvesting: In many arid and semi-arid parts of the world, water harvesting for dry land is a traditional water management technique to mitigate future water scarcity. In the event of climate change, preserving rainwater and floodwater can boost yields and lower the risk of crop failure, thereby boosting the productivity of arable land. In India, neglected land unsuitable for any other crop is typically used to produce cashews as a rainfed crop. The cashew plant is severely stressed by rain from January to May, which has a negative impact on fruit set and flowering. Rainwater harvesting, in situ soil and water conservation, and cashew plant availability during the critical season are crucial for successfully gathering rainwater. With the right soil and water conservation techniques, such as modified concrete bunds or coconut husk burial in staggered trenches created across the slope, the barren land, even on steep slopes, may be efficiently used for cashew production (Rejani and Yadukumar 2010). Rainwater harvesting may be done in two ways. Rainwater is traditionally stored on surfaces for later use. Check dams, ponds, subterranean tanks, and other similar structures were employed. Rainwater collection with a novel concept: recharge to groundwater. Various techniques are employed for replenishing groundwater. One of the key techniques for preserving rainfall where it falls is on-site water collecting. Rainwater is often conserved by farmers using a variety of soil moisture management measures, which in turn replenishes groundwater. The involvement of the public is crucial to water conservation. It is imperative that the stakeholders receive the appropriate training to develop their water conservation knowledge and abilities.

3.4 Soil Management Strategies

Mulching of horticultural crops: Mulching, using raised beds and shelters, and preventing soil erosion are some of the crop management techniques that assist preserve soil moisture and shield crops from flooding, severe rains, and extreme heat. High-value vegetable production systems frequently employ both organic and inorganic mulches. These protective covers lessen soil runoff and erosion, lower soil temperature, and reduce evaporation. Keep fruits away from the soil and try to keep weeds away. Up to 25% less water can be used for irrigation. Mulching with organic materials can improve the structure, fertility, and other characteristics of the soil. In tropical rice-growing regions, rice straw is widely available and advised for summer tomato cultivation. Organic mulches are often used to inhibit the development of weeds.

Mulch not only inhibits weeds but also keeps soil moisture levels higher than unmulched soil since weed germination is influenced by temperature and soil moisture (Sharma and Achraja, 2000). The impact of several organic mulches (chopped wheat straw, peat, wood chips, grass and wood chips, and wood chips) that had been kept for eight years and were spread out in layers of five and ten centimeters on weed emergence was investigated by (Jodaugiene*et al.,*2006). Weed germination was decreased by all organic mulches. Mulches proved beneficial at the time when weeds were heavily germination-prone. The most effective materials for reducing weed germination were wood chips, straw, and peat. In India's varied climate, mulching enhanced the development of eggplant, okra, bottle gourds, round melon, ridge gourds, and sponge gourds as compared to the non-mulched controls (Pandita and Singh, 1992). According to (Singh *et al.*, 2009), using drip irrigation in addition to black polyethylene mulch increased tomato productivity by an additional 57.87 t/ha. Dark-colored plastic mulch combined with rice straw is advised in lowland tropical regions with high temperatures (AVRDC, 1990). Rice straw insulates the plastic from direct sunlight, and maintains the soil temperature from rising too high throughout the day, while dark plastic mulch blocks sunlight from penetrating the soil's surface. Vegetables like tomatoes suffer from yield losses brought on by heavy rainfall during the hot rainy season. Simple clear plastic rain shelters boost tomato yields by preventing flooding-related water logging and rain-related impact damage to mature tomatoes (Midmore*et al.*, 1992).

Conservation tillage: It is important to encourage low tillage and the preservation of permanent soil cover, since these practices can boost soil organic matter and lessen the effects of flooding, erosion, drought, intense rain, and winds. Organic farming, risk-coping production methods, and conservation agriculture are a few areas that may be investigated. By aerobic mineralization and low tillage, intensive soil tillage decreases soil organic matter, whereas crop residues and cover crops help to maintain a permanent soil cover, which raises soil organic matter (Rahn *et al.*, 2003). Conservation tillage techniques have been shown to boost farm system resilience and enhance formers' ability to adjust to climate change (Lal, 1987). Simultaneously, these methods have the potential to decrease carbon emissions caused by plowing and also absorb carbon through residue assimilation and decreased erosion. Farmers in the Niger Delta have resorted to several strategies to adapt to climate change. Of these, 80.20 percent were planted with early rainfall, 77.20 percent adopted mixed farming, and 75.80 percent used proper seed preservation. Comparably, 74.20 percent of farmers employed inorganic manure; 72.0 percent used organic manure; 71.80 percent used cover crops; and 67.50 percent of farmers employed more weeding of cropland. To mitigate the consequences of climate change, other notable adaptation actions identified included protecting water sheds/mulching (64.50%), learning about climate change (59.20%), using low or zero tillage (57.20%), and afforestation (56.0%) (Nzeadibe*et al.*, 2011).

3.5 Grafting for Stress management:

Plants can grow more effectively under stress when vulnerable plants (scions) are grafted on tolerant plants (rootstocks), particularly when salt and drought affect the plant. Initiated in the 1950s, eggplant grafting was succeeded by cucumber and tomato grafting in the 1960s and 1970s (Edelstein, 2004). Melons grafted onto hybrid squash rootstocks were shown to be more salt-tolerant than non-grafted melons. (Romero *et al.,* 1997). The majority of vegetables cannot withstand too much moisture in the soil. For instance, tomatoes are thought to be one of the vegetable crops that is most vulnerable to too much water. Genetic diversity for the capacity to withstand excessive soil wetness has not been sufficient to stop losses up to this point. Many eggplant accessions are very resistant to floods (Midmore*et al.,* 1997). As a result, eggplant rootstocks that have been shown to have a high tolerance to excess soil moisture and strong grafting compatibility with tomatoes can be used to increase the flood tolerance of tomatoes. Certain genotypes of eggplant are resistant to drought, therefore in addition to offering protection against flooding, eggplant rootstocks can also offer protection against low soil moisture stress.

4. Climate-Resilient Horticulture: Technological Developments

4.1 Precision Horticulture

With precision farming management techniques, yields may be increased without negatively impacting the ecosystem while also reducing the quantity of nutrients and other crop inputs. It is intimately related to the socio-economic and environmental components of the production system and deals with the management of variability in the dimensions of both time and space (Mondal *et al.,* 2011). Precision farming is appealing, and its fundamental principles naturally raise expectations that farming inputs may be used more efficiently, improving profitability and producing less harm to the environment (Hakkim*et al.,* 2016). Today's advancements in precision farming have the potential to supply tomorrow's environmentally friendly agriculture with the necessary technologies. Precision farming can significantly increase yields while requiring less external input, particularly for small farmers in developing nations.

Remote sensing: A collection of methods known as remote sensing uses the reflection or emission of light from plants or soil to gather field data without the need for physical contact. Vegetation indices in Pennsylvania have been computed using light reflection, whether it is artificial or solar. The normalised difference vegetation index (NDVI), practical for low-chlorophyll fruits and canopy imaging, is the most often used vegetation indicator. In good agreement with leaf chlorophyll measured chemically are a number of additional indicators that may be computed and are already in use (Richardson *et al.,* 2002).Electronically sensed data, acquired using satellite or airplane, that includes crop electromagnetic emittance and reflectance data can offer valuable insights into several aspects such as soil health, plant development, weed infestation, and so on. Programs for crop management that are customized to a certain place might benefit greatly from this kind of knowledge since it is affordable. This technology is helpful for precision farming since it makes it simple to obtain data on field parameters (Narayan, 2005).

4.2 Use of drones and sensors

DRONE (Dynamic Remotely Operated Navigation Equipment), also known as UAV, is a device that may be flown manually using radio signals via a remote control or smartphone app or automatically using GPS coordinates and autopilot to follow a predetermined course. The Indian government has declared in recent statements that it is focusing on boosting drones in the agricultural sector. The government of India intends to utilize "Kisan" (Hindi for farmers) drones to expand the nation's agricultural industry, according to the federal budget for 2022- 2023 (Kedari*et al.,* 2017). Large-capacity drones have the potential to start a revolution since they may be used to deliver products, such as fruits, vegetables, and fish, straight from farms to markets (Rani *et al.*, 2019). Growers may use drone-based aerial information in a variety of ways to manage their crops, even if they haven't implemented precision agriculture equipment on their property (Zhang and Kovacs 2012). Agricultural drones are drones that are used in agriculture to monitor crop growth and assist improve crop productivity (Joshi 2020). Because these drones have digital image capability and advanced sensors, farmers may employ them to help them gather their fields. According to (Shaw and Vimalkumar, 2020) this kind of technology may gather data that may be utilized to raise farm production and agricultural output.

4.3 Controlled Environment Agriculture (CEA)

Technologies for controlled environment agriculture provide several advantages over traditional farming. Crop production and nutritional quality are increased by optimizing environmental parameters that control plant development, such as light, temperature, CO2 concentration, humidity, and nutrients (Sharath Kumar *et al.,* 2020). Because crops are cultivated indoors in a controlled environment, year-round food production is possible with CEA systems, regardless of weather conditions. In addition, dense metropolitan areas—which currently house more than half of the world's population—can be the location of controlled environment agriculture systems (Food and Agriculture Organization, 2017). According to (Kalantari *et al.*, 2018), transportation's food miles and environmental externalities can be greatly decreased when CEA farms are close to urban customers.

Vertical farming and greenhouses: Growing crops inside of buildings coated in a transparent substance to shield them from harsh weather and bad climate conditions is known as greenhouse agriculture. Apart from greenhouses, there are alternative methods of sheltered agriculture such as net houses, low and high tunnels, and row covers. Controlled environment agriculture, or CEA, is made possible by greenhouse technology, which provide horticulturists the ability to adjust vital growth conditions including light, humidity, and temperature. Greenhouses are essential for climate-smart horticulture because of their controlled environments, which act as a buffer against external climatic fluctuations. China created the solar greenhouse, a well-liked, low-cost building with plastic glass (Gao *et al.,* 2010). The province of Liaoning is where these energy-efficient or lean-to greenhouses started (Jiang *et al.*, 2004).

Heating system in greenhouses: The solar greenhouses are passively heated by sunshine throughout the day and have a sizable roof surface along the south side. To retain heat within the greenhouse at night, a thermal blanket is draped over the building. The northern brick wall also keeps heat within the building. In China's colder northern areas, the approach proved extremely effective in raising greenhouse output (Chen *et al.,* 2000). In the winter, northern areas—especially those north of 40°N often use greenhouse heating (Nemali, 2021). A greenhouse can be heated using artificial (active) and natural (passive) techniques. While geothermal and solar heating are natural processes, artificial heating is powered by energy, fuel, or wood. A primary source of heat for greenhouses is solar radiation in the short wavelength range. The understanding of heat input and loss from greenhouses has grown since William Herschel's 1800 discovery of infrared radiation. The idea of infrared radiation serving as a heat source was used to fruit walls in England, France, and the Netherlands throughout the 17th century. These walls warm up by collecting short-wave solar energy throughout the day and sending long-wave infrared radiation into the night time (De Decker, 2016).

Cooling system in greenhouse: Because of the sun's powerful radiation, greenhouse temperatures can rise significantly throughout the summer in tropical and subtropical climates. If the heat isn't evacuated, greenhouse temperatures can get extremely high. A wide range of techniques, including evaporative cooling, forced ventilation, natural ventilation, and shade, are used to produce greenhouse cooling. The simplest approach is shade, however, this reduces the amount of light that plants receive. Thus, in addition to shade, various techniques including exhaust fans, cooling pads, and natural ventilation are employed. Evaporative cooling is a common technique used in contemporary greenhouses to reduce temperature. Heat exchange between heated air and cool water is the basis of the principle. When heated air and cool water come into contact, heat transfer occurs and the air temperature drops. By taking up heat from the atmosphere, water evaporates, raising humidity. Evaporative cooling was first applied in Arizona in the US. Arizona's first drip-style evaporative cooler was constructed in 1908 by Oscar Palmer Sr. (Cunningham, 1985). In the United States, greenhouses were ventilated using fans or forced air until the 1950s. In India, Agricultural research centers and experimental farms in states like Maharashtra, Karnataka, Tamil Nadu, and other regions of North India were among the first to utilize evaporative cooling in greenhouses. Because of their substantial agricultural production and the existence of horticultural research and development institutes, these regions were among the first to adopt contemporary greenhouse technology, including evaporative cooling (OpenAI, 2024).

Hydroponics, Aeroponics, Aquaonics: In the past, greenhouses grew crops in containers by adding organic media to locally available soils, such as loam. But soil-based media were bulky and needed sterilization, which drove up expenses. Crop production in commercial greenhouses grew considerably with the invention of the hydroponic farming technique (Singh, 2017). Plants can be grown hydroponically (without soil) by utilizing mineral fertilizer solutions in an aqueous solvent. Deep water culture (DWC), drip systems, nutrient film technique (NFT), and other methods can all be used to supply a nutrient-rich water solution to plants such that the roots are exposed to it. In controlled environment agriculture, hydroponics is used to grow high-value crops like lettuce, spinach, and herbs. It is becoming more and more popular in urban farming, especially in places like Bangalore, Delhi, and Mumbai (Tiwari *et al.*, 2015) In the 1950s, soilless substrates gained popularity as horticultural medium (Kitir *et al.*, 2018). This can be linked to studies carried out in the 1950s at the University of California (Baker, 1957). The utilization of organic material, such peat, as a good soilless media for plant growth was subsequently demonstrated by several research (Carlile *et al.,* 2019).

Aeroponics is a soilless growing method in which plants are suspended in midair and finely misted with nutrient-rich water sprayed directly into their roots. This technique maximizes the amount of oxygen that reaches the roots while using less water. The method reduces the danger of soil-borne diseases, grows plants quickly, and uses water and nutrients with extremely high efficiency. Although aeroponics is still in its infancy in India, it is being investigated for high-value crops and scientific reasons, especially in vertical farming setups and in metropolitan areas with limited space (Gupta *et al.,* 2019).

Aquaponics is a symbiotic system that blends hydroponics growing plants without soil and aquaculture, which means breeding fish. The plants aid in purifying the water that is returned to the fish tanks, and the waste that the fish create feeds the plants (Sulaiman *et al.,* 2020). It is an integrated system that generates fish and plant crops while minimizing waste and utilizing resources to the fullest. India is investigating aquaponics as a sustainable agricultural method, particularly in regions where water conservation is essential. It is considered a possible technique for organic farming as well (Ghosh, 2018).

4.4 Genetic engineering and Biotechnology

The implications of biotechnology include the breeding of plants to increase and stabilize yields by strengthening their resistance to pests, insects, and other potential threats; to combat drought and other environmental challenges like cold and acidic soil; and to enhance the nutritional value of a variety of foods. Numerous important genes have been found via genetic and molecular techniques, and new knowledge is always being discovered. The genes that regulate the CBF cold-responsive pathway are among them. These genes and the DREB1 genes combine several elements of the cold acclimation response to withstand low temperatures (Sanghera *et al.,* 2011).

Molecular markers speed up and improve the development of stress-tolerant and higher-yielding cultivars for farmers in developing nations by facilitating the effective introduction of superior alleles from wild species into breeding programs and enabling the pyramiding of genes controlling quantitative traits. Many QTLs for stress tolerance in tomatoes have been found, such as those for water-use efficiency in S. pennellii and S. pimpinellifolium, which are sources of salt tolerance. The majority of phenotypic variation is explained by a small number of important QTLs, suggesting that marker-assisted selection (MAS) may be used to improve salt tolerance. The amalgamation of QTL analysis with gene discovery and genetic network modeling will provide a thorough comprehension of stress tolerance, enable the creation of valuable and efficient markers for marker-assisted selection, and pinpoint potential genes for genetic engineering (Wani *et al.,* 2008.

One extremely useful use of biotechnology is the production of disease-free plants, which may be achieved using the micropropagation process. Bananas, strawberries, and stevia are among these types of plants. Usually, bananas are produced in nations where they become a significant source of food, employment, and/or money. By using the tissues of healthy banana plants, micropropagation may be used to create disease-free banana plantlets. It has all the makings of a ground-breaking method that is both reasonably priced and simple to use (Jain *et al.,* 2021).

5. Challenges to implement resilient Horticulture

A wide range of issues have emerged in response to the complex effects of climate change on agriculture, necessitating the development of innovative and forward-thinking strategies for sustainable solutions including technological ones like restricted availability of resilient crop varieties and poor water management infrastructure. Adoption is made more difficult by financial obstacles such as large upfront expenses, unclear returns, and a lack of funding. Significant obstacles include gender inequalities, social opposition to altering customs, and issues with community involvement. Agricultural output is threatened by dwindling water supplies, a reduction in arable areas, and a shortage of essential inputs like fertilizers. Crops and biodiversity are at risk from pests whose distribution and behavior are influenced by the changing climate. Widespread adoption is further hampered by uneven governmental support, inadequately funded extension services, and unstable market access. These problems are made worse by environmental variables including erratic weather patterns and degrading soil, and advancement is further hampered by a lack of research and technological transfer. This highlights the need for supporting policies, market connections, and novel financing methods.

6. Conclusion

Climate-resilient horticulture is a critical strategy for ensuring food security and maintaining agricultural output in the face of climate change. This strategy entails modifying horticulture methods and technology to reduce the effects of extreme weather events, changing climate patterns, and environmental stresses. Key strategies include developing and implementing climate-resilient crop varieties that can withstand drought, floods, and pests; implementing efficient water management techniques such as drip irrigation and rainwater harvesting; and employing protected cultivation methods such as greenhouses and shade nets. Precision agriculture, which employs data-driven insights to improve resource usage, and integrated pest management (IPM) are also important components. Furthermore, boosting community participation, improving farmer education, and establishing supporting policy frameworks are critical to wider adoption of these methods. Despite the hurdles, which include high initial costs, knowledge shortages, and societal hostility, the transition to climate-resilient horticulture is critical to the sector's long-term viability.

Adapting horticulture to the harsh facts of climate change through creative techniques and technology is not an option, but a need for agriculture's future. While the problems are enormous, they may be met by a coordinated approach that involves investment in research and development, improved infrastructure, financial assistance for farmers, and strong legislative measures. By adopting climate-resilient horticulture, we can safeguard agricultural livelihoods, assure food security, and contribute to the overarching objective of sustainable development in a changing environment.

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